Fire Safety Journal 87 (2017) 37–48

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Fire whirls in forest fires: An experimental analysis

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ARTICLE INFO

Keywords:
Fire whirl
Fire tornado
Forest fires
Wildfire
Extreme fire behaviour
Fire safety
Forest fuels

ABSTRACT

This work presents a study on the formation of fire whirls with vertical axis on wildfires at laboratory scale. A particularity of the study is the use of typical forest fuels instead of fossil fuels as seen in some of previous studies on this topic. The forest fuels tested in the experiments were dead needles of Pinus pinaster, straw of Avena sativa, dead leaves of Eucalyptus globulus and a mix of shrubs mainly composed by heather (Erica australis) and gorse (Pterospartum tridentatum). The experimental results of the tests with and without forced flow inside a fire whirl generator were compared with tests in similar conditions out of the generator. It was possible to evaluate the effects of fuel bed size, bulk density and external vorticity on several parameters like flame height and diameter, mass decay and heat release rate. The results show that forced flow increases dramatically the burning rate and reduces the time needed to achieve a high rate of energy release. Comparison with results of other sources show that the flames that are generated in the present fire whirl generator are in a transition from fire whirl to pool fire regime and that it is possible to scale up some flow and thermal properties of field scale fire whirls and to derive predictive models on the basis of laboratory scale experiments.

1. Introduction

Forest fires are a natural disaster with great social, economic and environmental impact, making the study and understanding of fire behaviour essential for their successful management. In some circumstances forest fires can cause great devastation and endanger citizens and those who are in charge of suppressing them. It is recognized that situations in which fires spread under extreme weather and topography conditions are more likely to cause wide destruction and produce accidents [1,2].

Fire whirls are a phenomenon in which the fire under certain conditions acquires a vertical vorticity and forms a swirl or a flame column with vertical orientation that is also designated as a fire tornado [3]. They are characterized by a very high rate of energy release, unexpected formation and erratic movement, making them one of the most extraordinary and dangerous phenomena associated with fire behaviour [3]. In their erratic movement fire whirls can transport fire to areas far from the place where they were formed and they can also contribute to spread the fire by spotting due to embers that are lifted in their core to great heights and transported far from the fire perimeter by wind.

Several studies have been conducted in order to understand better the conditions required for fire whirls to form and their role on the fire whirl properties. Reports describing the role of topography, fuels and weather on the formation of fire whirls, are important to better understand and predict this phenomenon [4]. For example, Alexander and Thomas [5] studied the conditions leading to the formation of a fire whirl that occurred during a fire near Santa Barbara, California, in March 1964. These authors stated that unstable atmosphere, high temperature at the ground level, a very low relative humidity, moderate winds and a large fuel load were defined as potential conditions for this phenomenon occurrence. In a general view, one of the main factors that contributes for the formation of fire whirls is the buoyancy force. Other studies with similar statements have been reported by several authors (e.g., [6–8]).

The thermodynamic and kinematic characterization of fire behaviour regarding the formation of fire whirls has been the subject of several studies on analytical [9–11], numerical [12,13] and laboratory experiments [14–25] over the past few decades. The earliest reported experimental studies were conducted by Emmons and Ying [14] in 1967 using a rotating screen to generate vorticity on a liquid (acetone) pool fire with only 10 cm diameter. The fire whirl created consisted of a rotating cylinder fuel rich inside and lean outside flame and the authors concluded that the mass loss rate increased with the increase of ambient air circulation. Other experimental studies have been performed, most of them using liquid and gas fuels. One of the few reported experimental studies of fire whirls formation using solid fuels was carried out by Martin [15] who employed cross-piled wood sticks with different dimensions and moisture content values to measure the burning rates in a cylindrical device in which the tangential inlet of air

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http://dx.doi.org/10.1016/j.firesaf.2016.11.004
Received 9 August 2016; Received in revised form 9 November 2016; Accepted 23 November 2016
Available online 01 December 2016
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Nomenclature

d	diameter (m)
h	height of container (m)
m	mass loss (kg)
t	time (s)
v	velocity (m s^{-1})
F	fan frequency (Hz)
H	low calorific power (kJ kg^{-1})
L	length of the flame (m)
M	dry mass (kg)
V	volume (m^3)
$\dot{m}$	mass loss rate (g s^{-1})
$\dot{Q}$	heat release rate (kW)

Greek symbols

β	packing ratio (-)
ρ	density (kg m^{-3})

Subscripts

o	initial
b	bulk
c	container
D	chaparral dead fuel
f	flame
fu	fuel
m	medium
M	maximum
i	inlet
in	inside
out	outside
s	solid particles

at the bottom could be controlled. They found that burning rates in cribs with fire whirls were 1.4–4.2 times greater than in cribs burning without whirl formation, although they reported that fuel particle density, bulk density, surface area to volume ratio, packing ratio and moisture content influenced the results, they did not study other parameters, such as flame height, that characterize and that are necessary to better understand this phenomenon.

A remark that is made on the study of fire whirls by various authors is the lack of data in this area through experimental studies at laboratory scale. In recent years great importance was given to develop experimental equipment capable of further study on this topic. As an example we mention the extensive experimental work performed recently by Lei et al. [16–19]. The experimental apparatus used in their studies was a square enclosure with 2 m×2 m×15 m made of tempered glass and open on the top. The vertical channel had 20 cm wide vertical gaps at the corners to induce tangential air entrainment by the flame produced by liquid fuel. Different sizes of fuel pans (diameters 10–55 cm) were used and the liquid fuel was n-heptane (97%). In [16] the dynamic differences between fire whirls and pool fires were shown, and correlations of the burning rate, flame height and temperature of fire whirls were established. It was concluded that the pool diameter has a great influence on the burning rates of fire whirls, as in general pool fires, and that the transition from laminar to turbulent burning occurs when the pool diameter increases. The study of quasi-steady burning rate of laminar and turbulent fire whirls was done in [17] establishing correlations based on the boundary layer theory, film theory and Chilton-Colburn analogy. Due to the flame instability observed in the previous studies, Lei et al. [18] explored the characteristics of the flame of fire whirls distinguishing the flame revolution and the flame precession. Experimental observations have shown that in the formation of a fire whirl, the entire fire is tilted and revolves around its axis of symmetry with increasing angular velocity.

Other example is the work done by Kuwana et al. [20–22] which gave a great contribution to the understanding of this phenomenon by reproducing experimentally at laboratory scale, fire whirls that occurred in real fires to study the mechanisms of formation of these fire whirls in different configurations. Examples are the fire whirl that occurred in Hifukushoato [20] in an open space and the case of fire whirls generated by the interaction between a line fire and the background wind as occurred in Brazil [22]. In [20] the Hifukushoato fire whirls were reconstructed at the 1/1000th scale using a large-scale wind tunnel and where lateral wind velocity was varied from 0.5 to 2 m/s to study its effect on fire-whirl formation. Different types of fire whirls formation in open areas where there was no combustible material were observed. The authors studied the influence of the lateral wind velocity and developed and validated a scaling law that predicts the critical wind velocity at which the most intense fire whirl was generated. It was observed too that in actual mass fires the occurrence of fire whirls is time-dependent, in contrast to well-controlled small-scale laboratory experiments, but this finding was not explored. In [22] it was verified that an appropriate scale model can successfully reconstruct the occurrence of fire whirls moving along a line fire and that a critical velocity was found to be proportional to the vertical buoyant velocity, which depends on the burning rate and length scale of the burning area. One point that was not discussed in that paper was the possibility of correlating the ratio between the critical velocity and the vertical buoyant force to the existence of a critical Froude number below which no fire whirls can be observed. It was stated in this study, but not confirmed, that a curved-shape geometry is necessary to generate moving type fire whirls.

An interesting study was conducted by Chuah et al. [23] on the formation of inclined fire whirls, i.e., fire whirls for which buoyancy cannot be the source of support. Fire whirls with this configuration are observed frequently in forest fires. In this study an adjustable support for producing inclined fire whirls in the laboratory was placed on the base of the fire whirl generator. It was shown that the flame length was independent of the inclination angle at a given burning rate. The upper section of the apparatus was modified to observe the influence of flame height for a certain burning rate and it was concluded that for the same burning rate the flame height can be changed. So, if the structures of fire whirls are sufficiently strong, they will be dominated by the rotation plus entrainment, rather than by buoyancy. So, the several mechanisms that can explain the formation of fire whirls have been a focus point to understand and predict the occurrence of this phenomenon, as shown by the studies of [20–23] mentioned above or, for example, the study of [25] in which it is shown experimentally that the counter-rotating vortex pair is a possible origin of fire whirls that occur downwind of a fire area and are shed downwind.

Although important research has been done to better understand the mechanisms and behaviour of fire whirls generation through theoretical or/and experimental studies, it is difficult to get results that are in accordance from different studies with similar analysis conditions (theoretical vs experimental for example), as shown by Hayashi et al. [24] that try to validate, reproducing in laboratory fire whirls at small scale with methanol, the relation between the flame height and the vortex structure that was studied by Chuah et al. [26]. In this work the Burke-Schumann-Burgers (BSB) model for small-scale fire whirls based on the assumption that vortex structures of fire whirls are able to be approximated by the Burgers vortex was developed. The results indicate that the vortex around the fire whirl cannot be

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